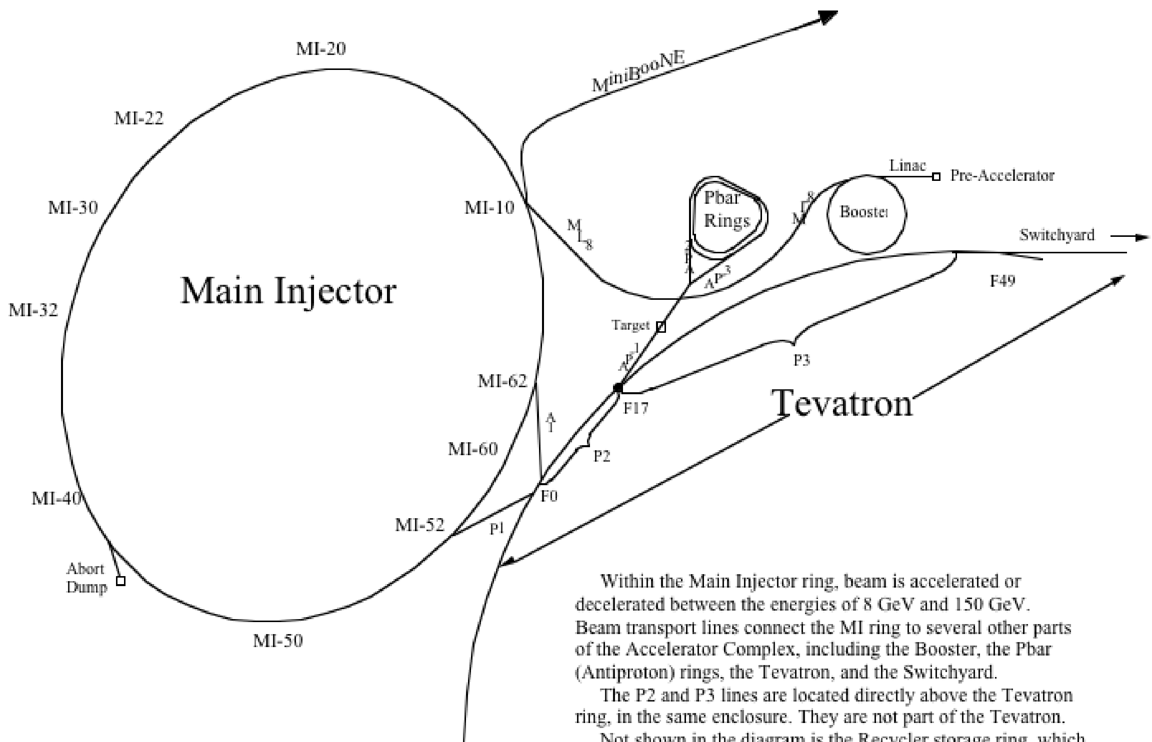
Chapter 1: Modes of Operation

A batch, a batch,
A Booster full of buckets
Old English nursery rhyme

Geography

The Main Injector ring is located in the southwest corner of the Fermilab site, adjacent to the Tevatron on one side and the Prairie Path bicycle trail on the opposite side. It is roughly elliptical in shape (Fig. 1-1). Beam transport lines connect the Main Injector not only to the Tevatron, but also to the Booster, Antiproton Source, Switchyard, and the Recycler Ring.



Within the Main Injector ring, beam is accelerated or decelerated between the energies of 8 GeV and 150 GeV. Beam transport lines connect the MI ring to several other parts of the Accelerator Complex, including the Booster, the Pbar (Antiproton) rings, the Tevatron, and the Switchyard.

The P2 and P3 lines are located directly above the Tevatron ring, in the same enclosure. They are not part of the Tevatron.

Not shown in the diagram is the Recycler storage ring, which is located directly above the Main Injector ring.

The distance between the Main Injector and Tevatron rings has been exaggerated in order to show the A1 and P1 lines more clearly.

Fig. 1-1
Fundamental Geography of the Main Injector

(The Recycler, not shown in Fig. 1-1, is located directly above the Main Injector in a shared tunnel.)

The Main Injector has such a central role in linking these areas that the other accelerators would be useless without it.

The Main Injector can accelerate or decelerate particles between the energies of 8 GeV and 150 GeV. The sources of the particles and their final destinations are quite variable and depend on the “mode of operation,” that is, what the Main Injector is being used for at the time. This chapter will describe the modes of operation, emphasizing how the accelerators link together and the path the beam takes during each type of operation. Most of the technical details will be deferred to later chapters so that readers have a chance to grasp the big picture first.

Main Injector, like all of the accelerators, has a numbering scheme that defines locations around the ring. In principle, you can locate every component in the tunnel through this convention. Main Injector can be thought of as having six major “mileposts” at more or less equal intervals around the ring: MI-10, MI-20, MI-30, MI-40, MI-50, and MI-60. MI-10 is the point where protons enter the ring from the Booster. The protons travel counterclockwise, and so the numbers increase in a counterclockwise direction. MI-60 is the region adjacent to the Tevatron.

At each of these major locations there is a service building that houses equipment related to the accelerator components downstairs. Service buildings also provide access to the tunnel.

In between the major mileposts, you find locations by intermediate numbers; for example, the service buildings on either side of MI-60 are MI-52 and MI-62.

The beam transport lines, which connect the different accelerators to each other, have their own names and their own set of location numbers. For example, locations in the MI-8 line, which transports 8 GeV protons from Booster to the Main Injector, are predictably assigned numbers beginning with “8.” Other beam lines are named for the type of particle transported: “P” for protons, or “A” for antiprotons. Protons leaving the Main Injector use the P1 line, originating at MI-52. (Do not be confused by the fact that antiprotons sometimes use the P1 line as well.) Antiprotons use the A1 line, originating at MI-62, to leave the Main Injector. The P1 and A1 lines both terminate at the F0 location of the Tevatron, which runs parallel to MI-60. Devices in the P1 line are given numbers beginning with a “7,” and device names in the A1 line begin with a “9.”

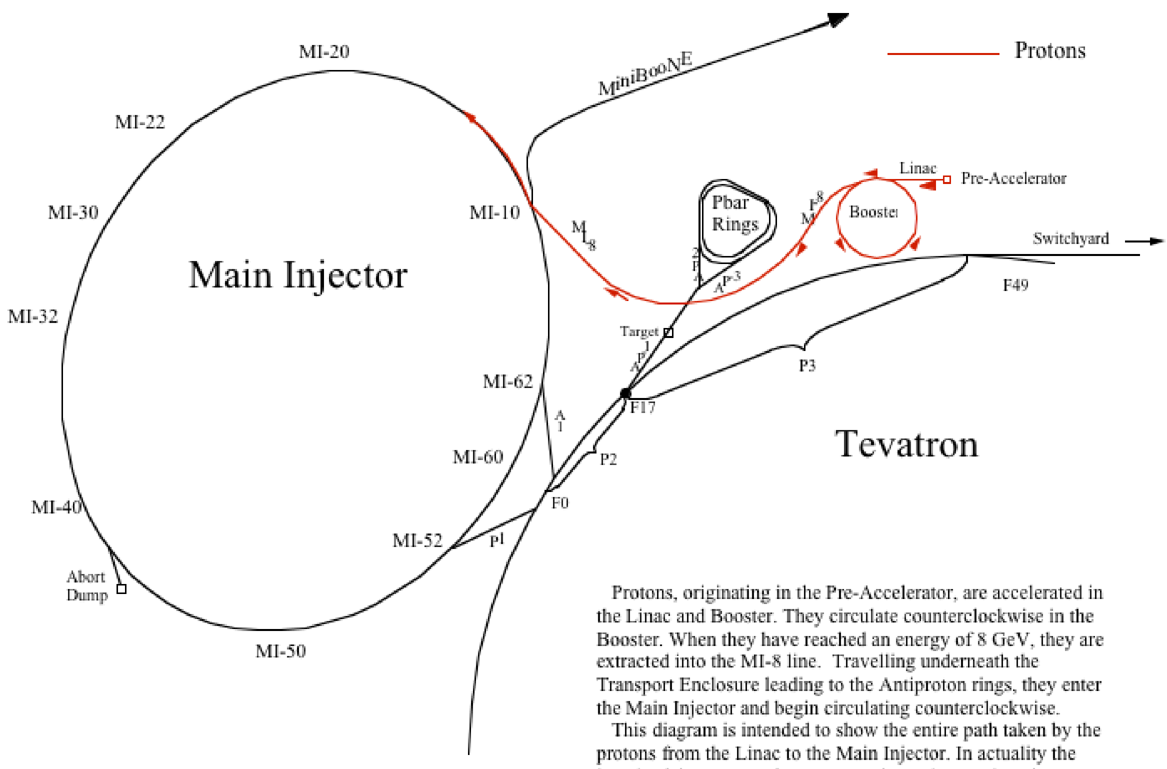
Two of the beam lines that deserve special mention are the P2 and P3 lines. Main Ring, like the Tevatron, was divided into six sectors, A through F. Although most of Main Ring has been disassembled and cannibalized, F Sector remains more or less intact. (Sometimes this old section of the Main Ring is referred to as the Main Ring Remnant.) It is used to link Main Injector to Switchyard in one mode, and to the Antiproton Source in another. Locations are designated F10 through F49. The boundary between P2 and P3 is at F17, which is where the beam line to the Antiproton Source branches off.

Main Injector accepts 8 GeV protons from the Booster, 8 GeV antiprotons from the Antiproton Source, or 8 GeV antiprotons from the Recycler. It can accelerate protons to 120 GeV for antiproton production, or for extraction to the Switchyard; it accelerates protons and antiprotons to 150 GeV during Collider Mode. When the Recycler is fully commissioned, it will accept 150 GeV antiprotons from the Tevatron and decelerate them to 8 GeV before injecting them into the Recycler to be stored. Finally, it is implicated in two neutrino experiments, MiniBooNE and NuMI.

One at a time, please!

The MI-8 Line

Linac accelerates protons to 400 MeV, and Booster accelerates them to 8 GeV. The purpose of the MI-8 line is to transport the protons from Booster to the Main Injector ring (Fig. 1-2). Extraction devices along the western perimeter of Booster kick the beam up and out of that machine. Permanent magnets (for the most part) guide the beam through the line. Generally, the magnets bend the beam to the right, avoiding the Antiproton Rings and eventually bringing the beam line parallel to the Main Injector ring. Injection devices at MI-10 place it onto the orbit it follows as it circulates around the Main Injector ring. The magnets in Main Injector keep the beam on that orbit.



Protons, originating in the Pre-Accelerator, are accelerated in the Linac and Booster. They circulate counterclockwise in the Booster. When they have reached an energy of 8 GeV, they are extracted into the MI-8 line. Travelling underneath the Transport Enclosure leading to the Antiproton rings, they enter the Main Injector and begin circulating counterclockwise.

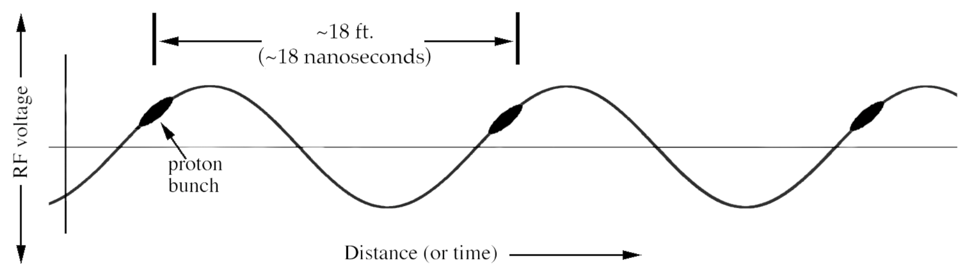
This diagram is intended to show the entire path taken by the protons from the Linac to the Main Injector. In actuality the length of the stream of protons can be no longer than the circumference of Booster, and during Collider Mode it is considerably shorter. Compare to Fig. 7-3.

Fig. 1-2
Protons into Main Injector

Once the beam is circulating and stable, it is accelerated to the desired energy by RF (radio frequency) systems located at MI-60. The details of RF will be discussed in a later chapter, but to understand the various modes of operation it is necessary to understand batches and bunches.

A batch consists of the beam that Booster accelerates and extracts in one cycle. A full batch has a length equal to the circumference of Booster, about 1,545 feet.

The beam does not form a continuous stream, but is bunched. This is because the protons congregate around a certain phase of the RF wave—called a bucket—and nowhere else (again, the reasons for this are explained in a later chapter). When beam is extracted from Booster, the RF wave is slightly over 18 feet long, and there is one bunch per bucket:



Because the wavelength of the RF wave is usually much smaller than the circumference of the accelerator, there are a number of bunches circulating in a machine at any given moment. The Booster, needs 84 bunches to fill all of the available RF slots around the circumference of the machine. The total sum of the bunches (or available buckets) is what constitutes a batch.

Main Injector Ramps

As soon as stable circulating beam is established, the acceleration process can begin. The RF adds energy to the beam. The magnets provide the constraining force that keeps the protons on the correct orbit, so that the current in the magnets increases to match the magnetic field to the energy of the protons (Fig. 1-3(a)). (It is the synchronous match of the magnets to the beam energy that entitles us to call our circular accelerators "synchrotrons.")

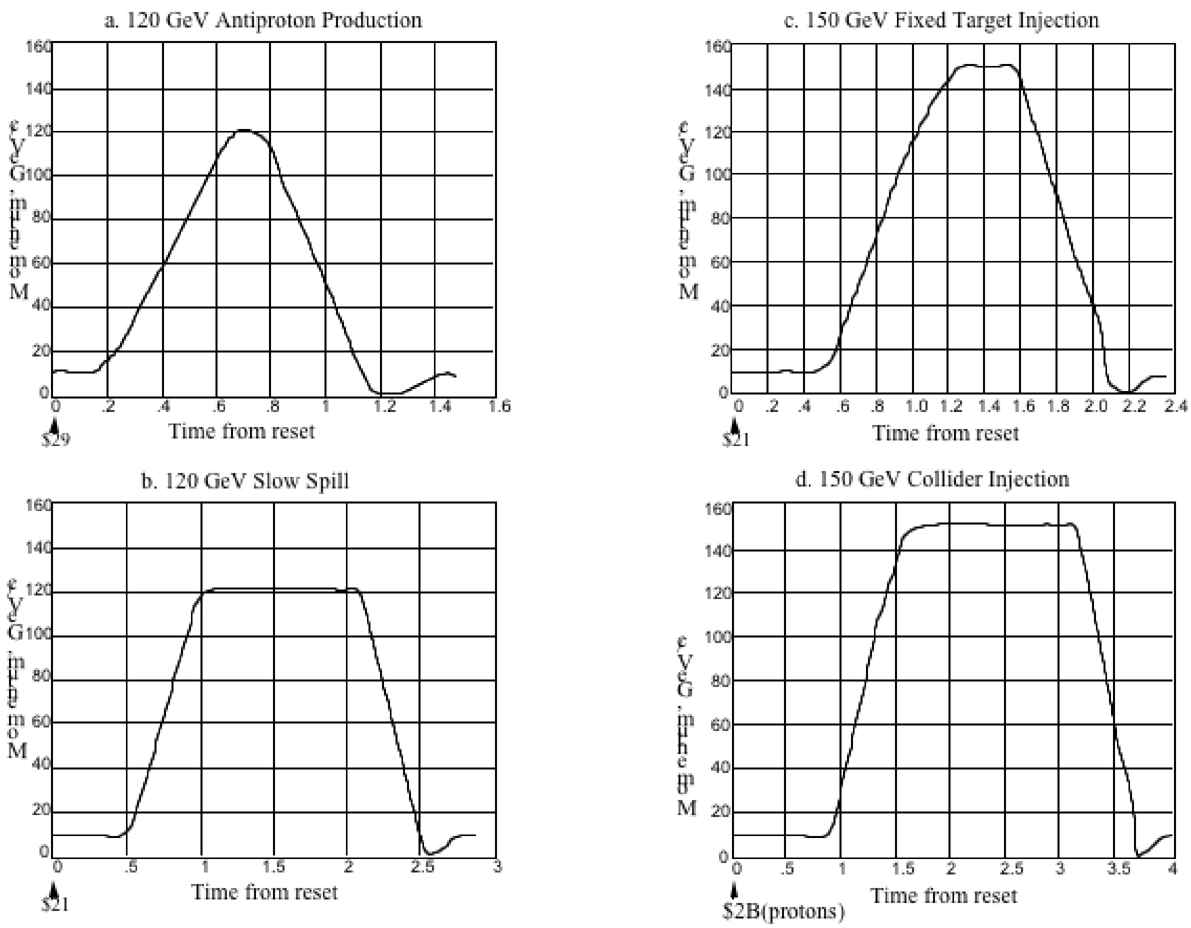
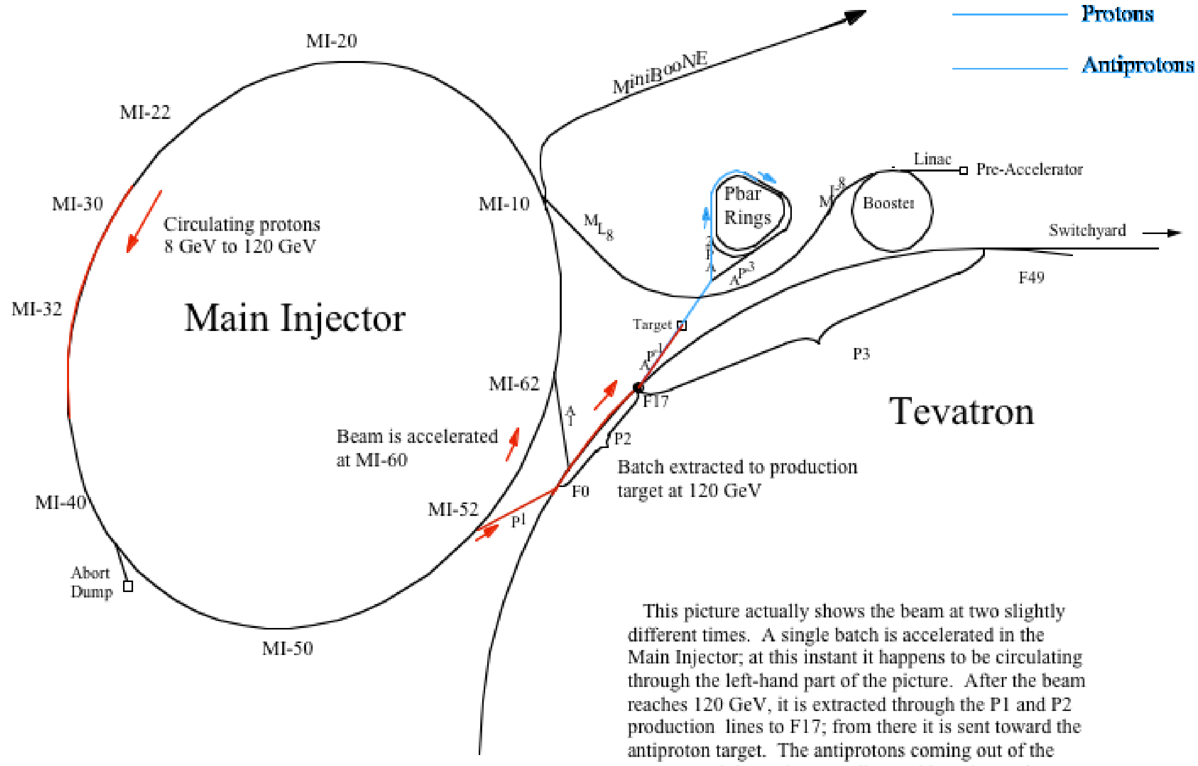


Fig. 1-3
Some Main Injector Ramps

Antiproton Production

Providing beam to the antiproton production target is one of the simplest tasks required of the Main Injector (Fig. 1-4). In this mode, a single batch of protons is accepted from the Booster at 8 GeV and accelerated to 120 GeV. The 120 GeV protons are extracted to the target, which yields 8 GeV antiprotons. (Scientists unable to pronounce the word "antiproton" use the synonym "Pbar," which will occasionally be used in this book to simplify graphics.)



This picture actually shows the beam at two slightly different times. A single batch is accelerated in the Main Injector; at this instant it happens to be circulating through the left-hand part of the picture. After the beam reaches 120 GeV, it is extracted through the P1 and P2 production lines to F17; from there it is sent toward the antiproton target. The antiprotons coming out of the target travel down the AP-2 line and into the Antiproton Source Rings, where they will be stored.

Fig. 1-4
Antiproton Production

Each of the modes of operation is initiated by a unique clock event. In the case of antiproton production, it is Event $29 (the "$" means that the number is hexadecimal). The clock events that trigger Main Injector cycles are designated by $2x, where x is a number 0 through F. These clock events come from the Time Line Generator (TLG).

When Event $29 occurs, it is normally accompanied by Event $14, which instructs the Booster to prepare one batch of beam. It requires exactly a thirtieth of a second for beam to be accelerated through Linac and Booster. It requires another couple of microseconds to transfer the beam out of Booster, through the 8 GeV line, and onto the Main Injector orbit.

The beginning of the acceleration is not linear; using a parabola softens what would otherwise be an abrupt change in the magnetic field. After the parabola, the rate of change does become linear for a while. As the final energy is approached, an inverted parabola eases the beam into "flattop." Flattop is a short period at the final energy during which the beam continues to circulate. In the case of the $29 cycle, flattop lasts for about 40 msec. Some modes of operation have distinct and complex tasks that must be completed during flattop.

When it is time for the beam to leave and make antiprotons, extraction devices in the Main Injector deflect the entire batch out of the ring and into the P1 line originating at MI-52. From there, the protons find their way into the P2 line; extraction from the P2 line into the AP-1 line takes place at F17. The AP-1 line carries them to the target.

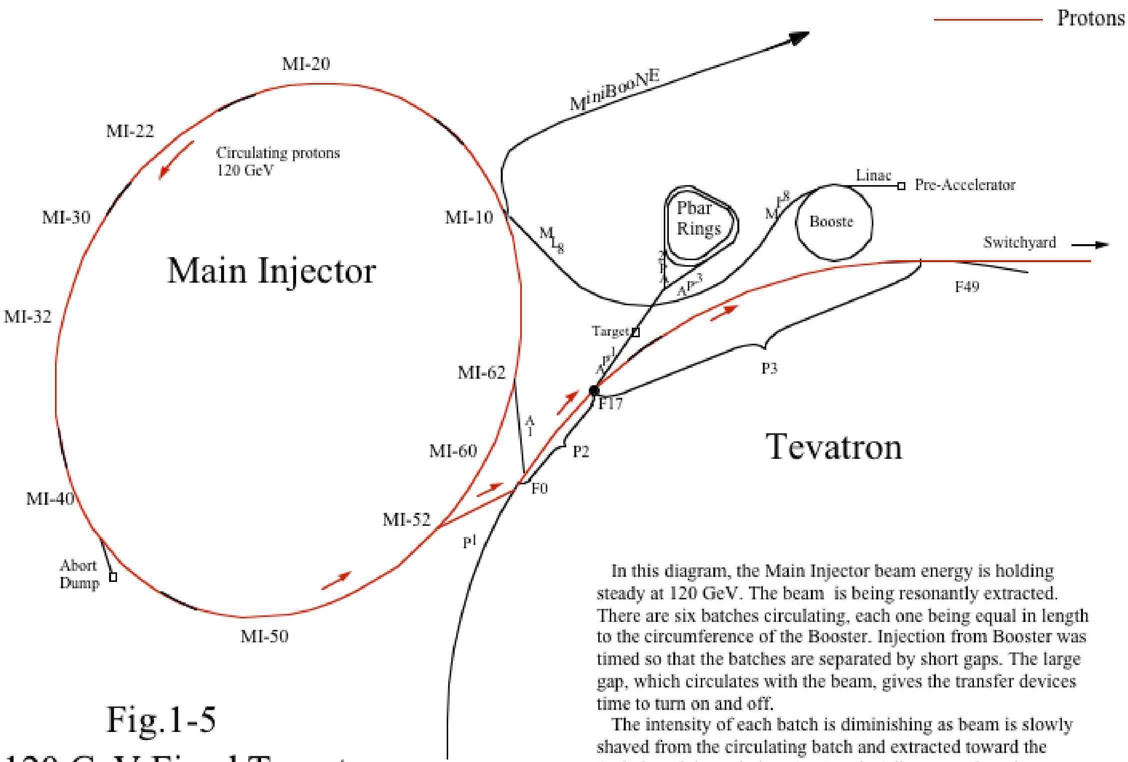
The entire 120 GeV antiproton production cycle takes about 2 seconds. To make as many antiprotons as possible, the target is continuously bombarded at the fastest possible rate for hours on end.

Fixed Target Modes

During Fixed Target operations, protons are accelerated to the desired energy and then extracted to a stationary target external to the ring. Extraction takes place from the Main Injector at 120 GeV (Fig. 1-5). The target can be anything from a sliver of metal to a flask of liquid hydrogen.

Extraction is initiated by clock event $21. It starts, as usual, with 8 GeV beam from the Booster. But this time, six full batches—all that the Main Injector can comfortably hold—are loaded in quick succession. When the Main Injector is full, the six batches are accelerated to 120 GeV.

At flattop, a process called resonant extraction is initiated. Resonant extraction is a rather complicated process and the details will appear in a later chapter. Basically the beam "spills" out of the machine over an enormously long time—say, two seconds—as opposed to being kicked out in a few microseconds as is the case with other modes of operation. The flattop time is extended accordingly (Fig. 1-3(b)).



In this diagram, the Main Injector beam energy is holding steady at 120 GeV. The beam is being resonantly extracted. There are six batches circulating, each one being equal in length to the circumference of the Booster. Injection from Booster was timed so that the batches are separated by short gaps. The large gap, which circulates with the beam, gives the transfer devices time to turn on and off.

The intensity of each batch is diminishing as beam is slowly shaved from the circulating batch and extracted toward the Switchyard through the P1, P2 and P3 lines. It takes about a second to extract all of the beam from the machine.

Fig.1-5
120 GeV Fixed Target

For the Fixed Target experiments, beam is deflected into the P1 line—the same line used for antiproton production—and likewise enters the P2 line. This time the extraction devices at F17 are turned off, and the protons travel the length of the P3 line into Switchyard.

Spill over a couple of seconds is considered “slow spill.” There is also “fast spill,” usually required by neutrino experiments, which occurs over a period of a few milliseconds. Keep in mind that fast spill is still much slower than single turn extraction.

One of the experiments that will use fast spill is NuMI (for Neutrinos from Main Injector). This experiment will be a very long baseline version of MiniBooNE, also designed to look for neutrino oscillations. Protons, at 120 GeV, will be extracted from Main Injector at MI-60 at a sharp downward angle. The neutrinos from the target, moving in the same direction as their proton parents, are measured before they disappear into the ground. Tracing a cord through the Earth, they travel 425 miles before encountering a onceabandoned iron mine in northern Minnesota. Here an experiment is being set up to measure what changes, if any, have taken place over the 425-mile baseline.

(Once upon a time, the sole purpose of the Tevatron was to provide beam for the Fixed Target experiments. At this time, it is not expected that this mode will ever be revived, but the following paragraph is retained for historical perspective):

[If higher energies are needed for fixed target experiments, the Tevatron can be called into service. The Tevatron can comfortably hold up to twelve batches of protons, but limitations on timing restrict the number of batches that can be transferred. The Main Injector is first filled with five batches, and accelerates them to 150 GeV—the minimum energy at which the Tevatron magnets can sustain a high quality field—and extracts them to the TeV in a single turn (Fig. 1-3(c)). The same P1 line discussed earlier is used for Tevatron injection, but the protons are switched over to the Tevatron at F0 before they have a chance to enter P2 or P3. Main Injector then drops back to 8 GeV and loads up another six batches to finish the job. When the 11 batches have been loaded, the Tevatron accelerates the protons to some energy between 800 GeV and 1 TeV. Spill from the Tevatron takes about 40 seconds out of a total of 80 seconds in a cycle; when the Tevatron returns to 150 GeV, the Main Injector will be ready to load the next 11 batches.]

MiniBooNE

MiniBooNE (Fig. 1-6), a direct descendant of an experiment done in Los Alamos during the 1990's, is studying the phenomenon of "neutrino oscillations." It requires large numbers of protons with an energy of 8 GeV. Beam is extracted from the Booster and sent down the MI-8 line, but just as it reaches the Main Injector ring, it is deflected north toward the experiment.

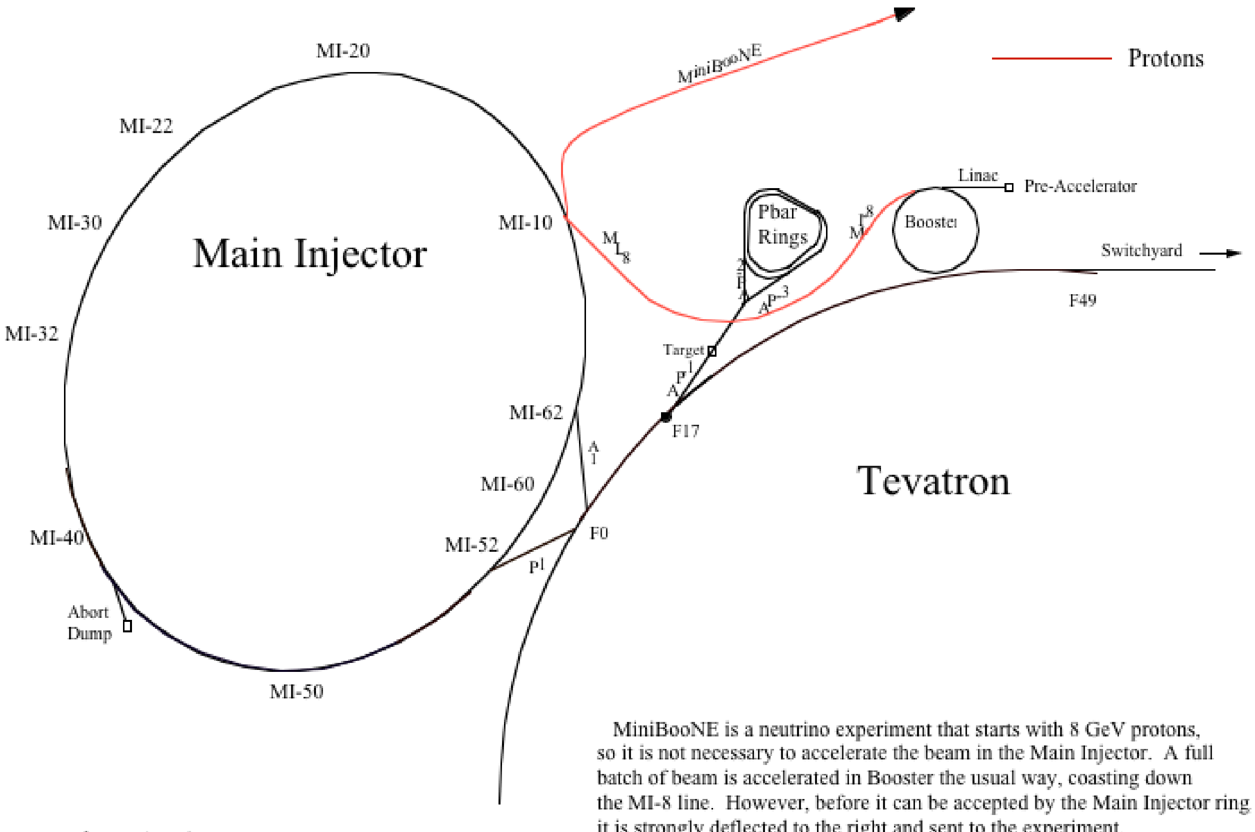


Fig. 1-6
MiniBooNE

Collider Operations

Collider Mode is the most complex scenario of all. Rather than striking a palpable, distinct target, protons circulating clockwise in the Tevatron collide with antiprotons that are circulating counterclockwise. The collisions take place in the Tevatron at an energy of 1 TeV (hence the name, although the current operational energy is actually only 980 GeV). Two large experiments hang like parasites around the Tevatron beam pipe at those points where the particles collide.

Main Injector must play several roles during Collider Mode. In addition to supplying 120 GeV protons for antiproton production, it must also feed the Tevatron protons and antiprotons at 150 GeV. To make matters worse, the experiments need "superbunches" more intense than any individual bunch than can be accelerated by Booster. A process called coalescing has been developed to create those superbunches; coalescing takes place at flattop in the Main Injector.

When protons are to be loaded, accelerated, and coalesced in the Main Injector, the sequence is initiated by Clock Event $2B (Fig.1-3(d)); for antiprotons, the event is $2A.

The following is a possible sequence of steps taken during a shot (the scientific term for loading the protons and antiprotons):

(1) One batch (84 bunches) of protons is accelerated to 8 GeV in the Booster.

(2) Only 7 (or so) bunches of the 84 are extracted to Main Injector; the remaining 77 are sent to the Booster dump. This group of bunches is a short batch or a partial batch, depending on who is doing the describing.

(3) The 7 bunches are accelerated to 150 GeV (Fig. 1-7).

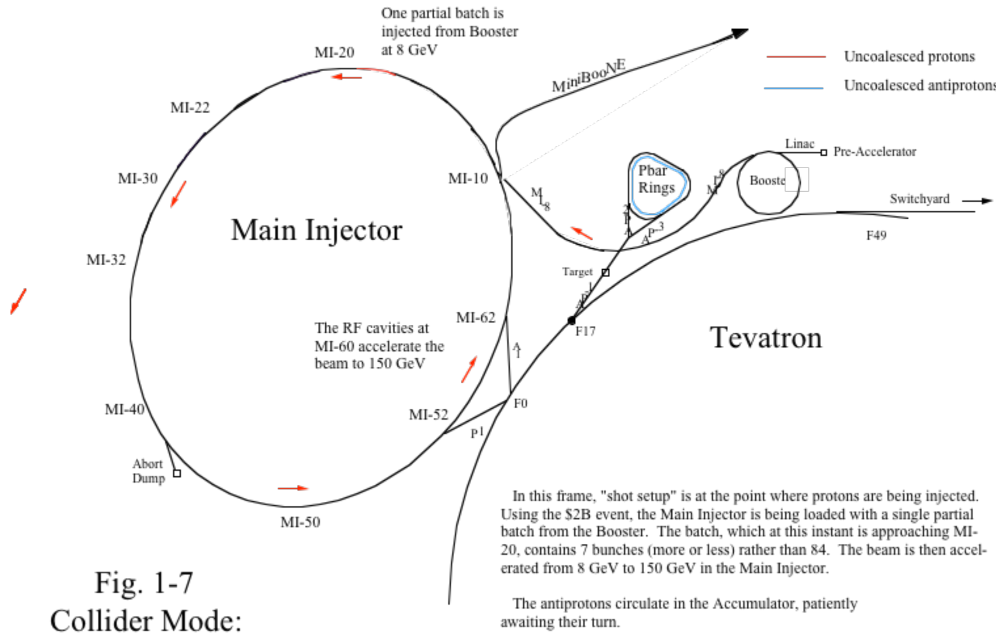


Fig. 1-7
Collider Mode:
Protons into Main Injector

(4) At flattop, the bunches are coalesced; that is, pushed together to form one narrow, high intensity bunch (Fig. 1-8).

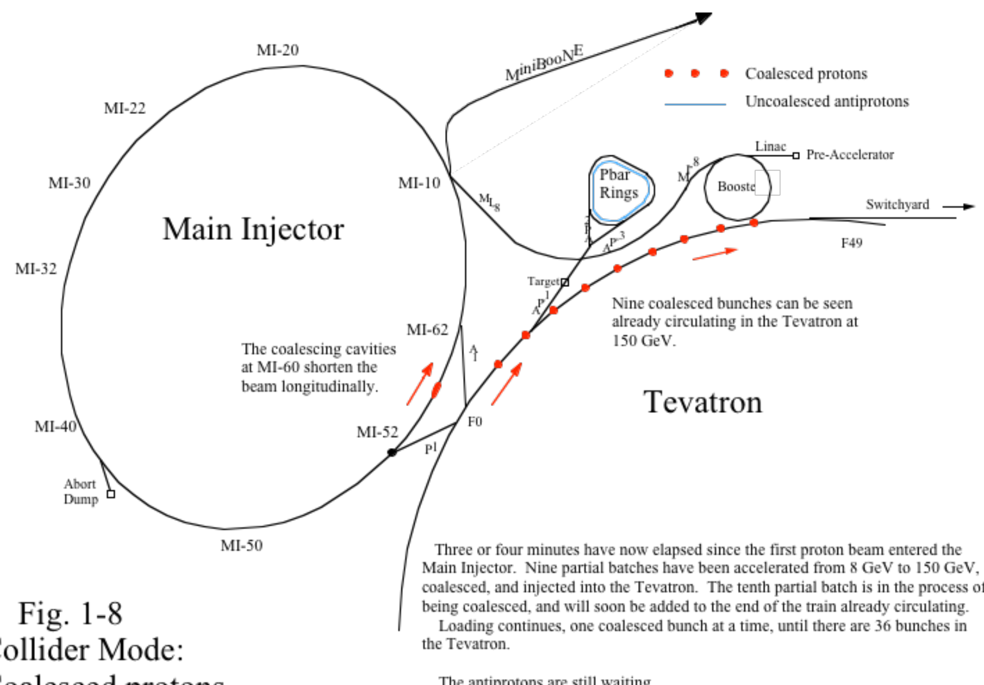


Fig. 1-8
Collider Mode:
Coalesced protons
into Tevatron

(5) The coalesced bunch is injected into the Tevatron in a single turn, passing through the P1 line on the way (Fig.1-8).

(6) The above steps are repeated until there are 36 coalesced proton bunches in the Tevatron.

(7) The 8 GeV antiprotons created from the production target have been patiently waiting, circulating in the Antiproton Source (more specifically, the Accumulator). The Accumulator RF systems create four groups of antiprotons, each group consisting of several bunches. They are extracted from the Accumulator via the AP-3 and AP-1 lines, and into the P2 line at F17 (Fig. 1-9). Note that once they are in the AP-1 line, they are traveling backwards from the route taken by the 120 GeV protons. They enter the Main Injector from the P1 line at MI-52 and begin to circulate clockwise, which is the opposite direction that protons would be taking.

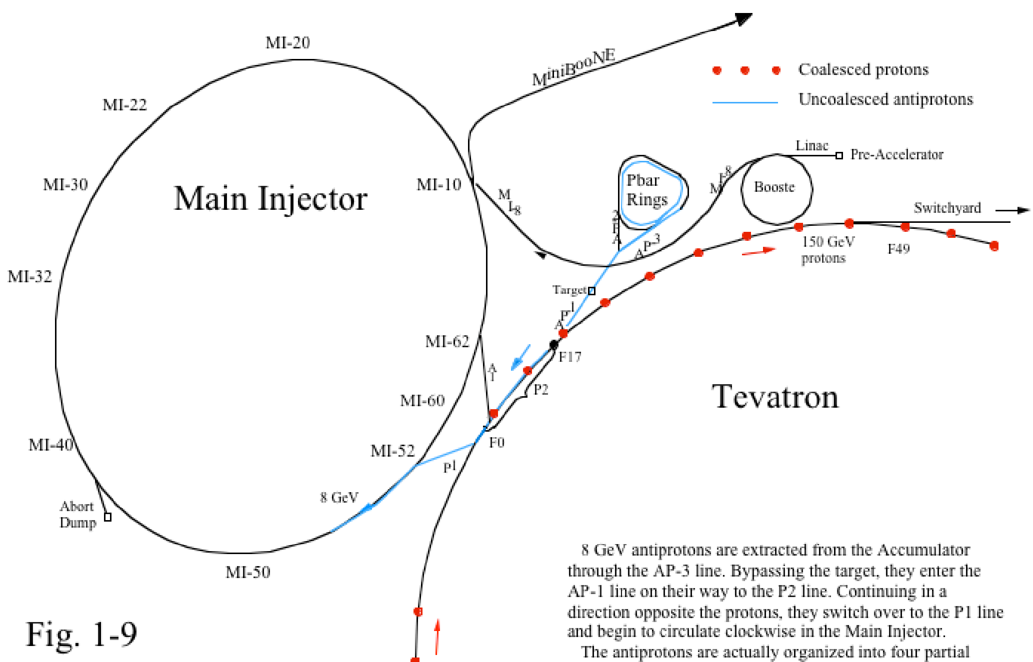


Fig. 1-9
Collider Mode:
Antiprotons into the
Main Injector

8 GeV antiprotons are extracted from the Accumulator through the AP-3 line. Bypassing the target, they enter the AP-1 line on their way to the P2 line. Continuing in a direction opposite the protons, they switch over to the P1 line and begin to circulate clockwise in the Main Injector.
The antiprotons are actually organized into four partial batches; for clarity the batch structure is ignored in this picture so as to emphasize the path of travel. Keep in mind that the protons are in the Tevatron and the antiprotons are in the beamlines above the Tevatron.

(8) The antiprotons are accelerated to 150 GeV (Fig. 1-10).

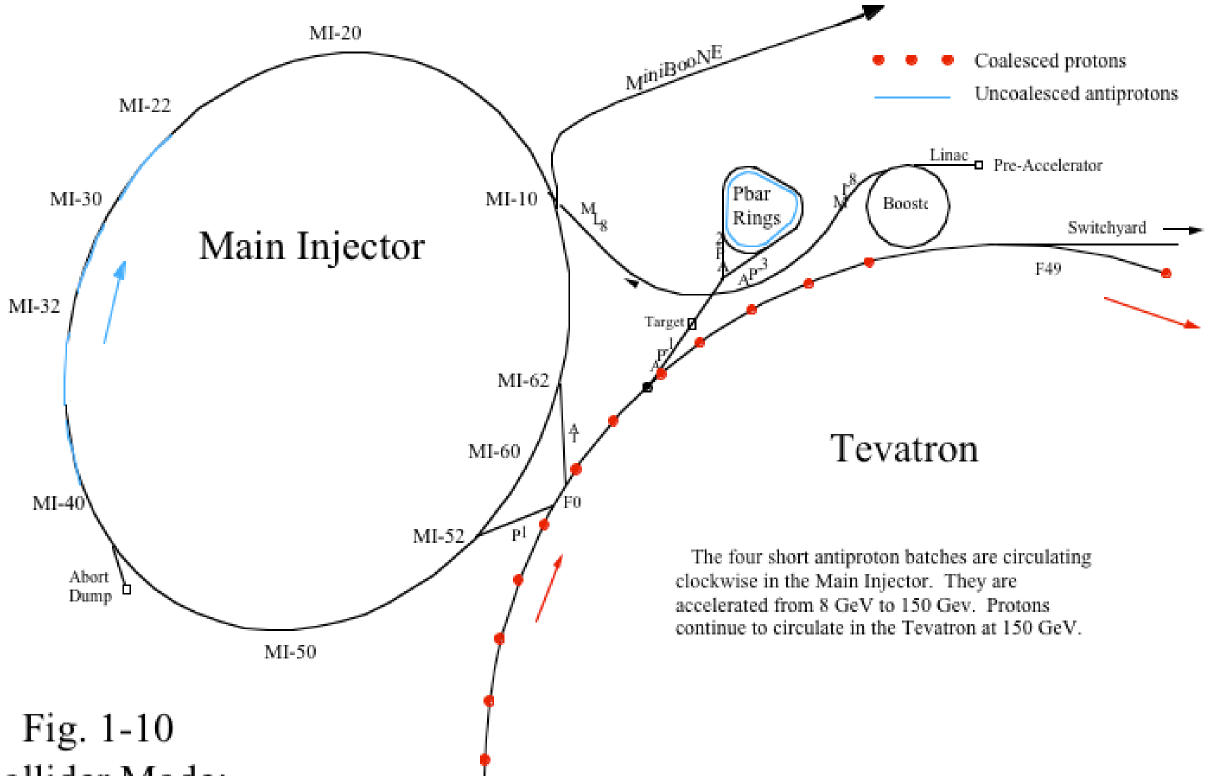


Fig. 1-10
Collider Mode:
Antiprotons Accelerated
in Main Injector

(9) The four groups of antiprotons are coalesced; four coalesced bunches are now circulating at 150 GeV.

(10) The four coalesced bunches are extracted to the Tevatron by way of the A1 line, originating at MI-62, and they enter the Tevatron at F0. (Notice that there is a gap in the string of proton bunches that allows room for the antiprotons.) The antiprotons are traveling counterclockwise in the Tevatron, opposite the direction taken by the protons. Both types of particles are now circulating in the Tevatron at 150 GeV (Fig. 1-11).

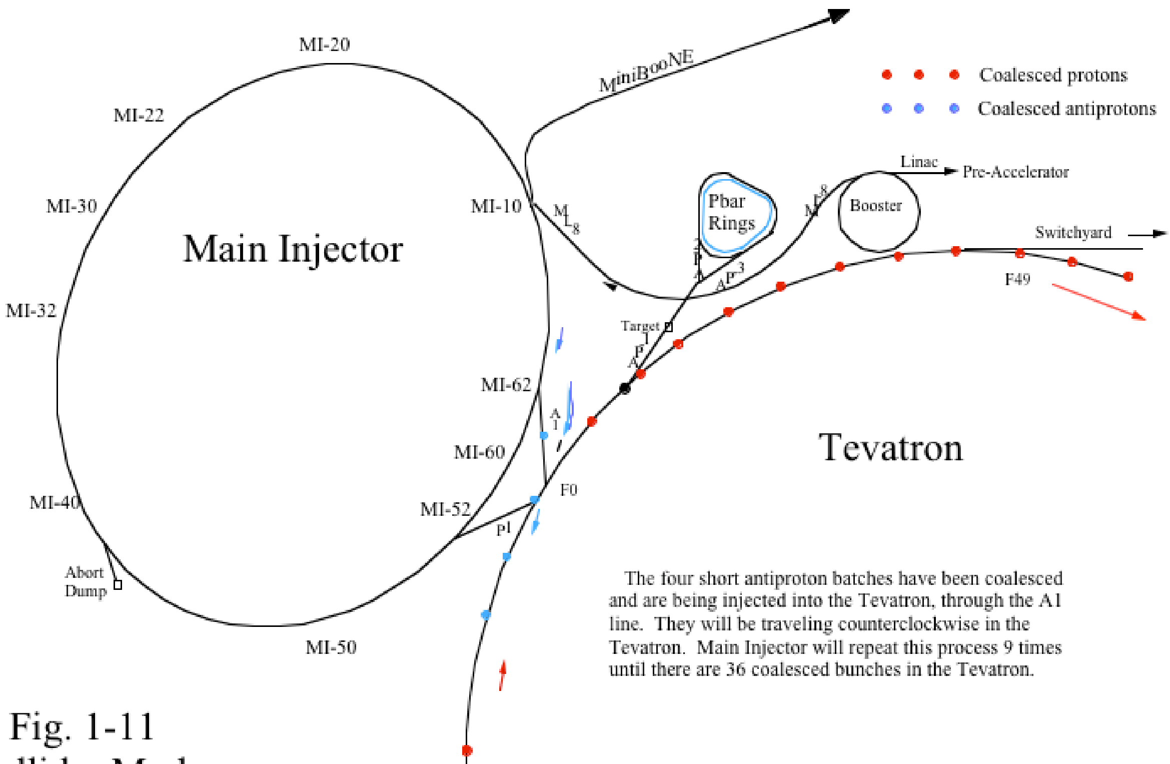


Fig. 1-11
Collider Mode:
Coalesced Antiprotons into Tevatron

(11) Main Injector drops back to 8 GeV for another four groups of antiproton bunches. The process repeats until nine shipments have been delivered. There are now 36 coalesced bunches of antiprotons and 36 coalesced bunches of protons circulating in the Tevatron.

(12) The Tevatron ramps to 1 TeV with all of the coalesced bunches. A 36X36 store is established, and the two particle detectors in the Tevatron ring begin to take data. The Main Injector is now free to return to stacking. A store is intended to last for at least several hours (Fig.1-12).

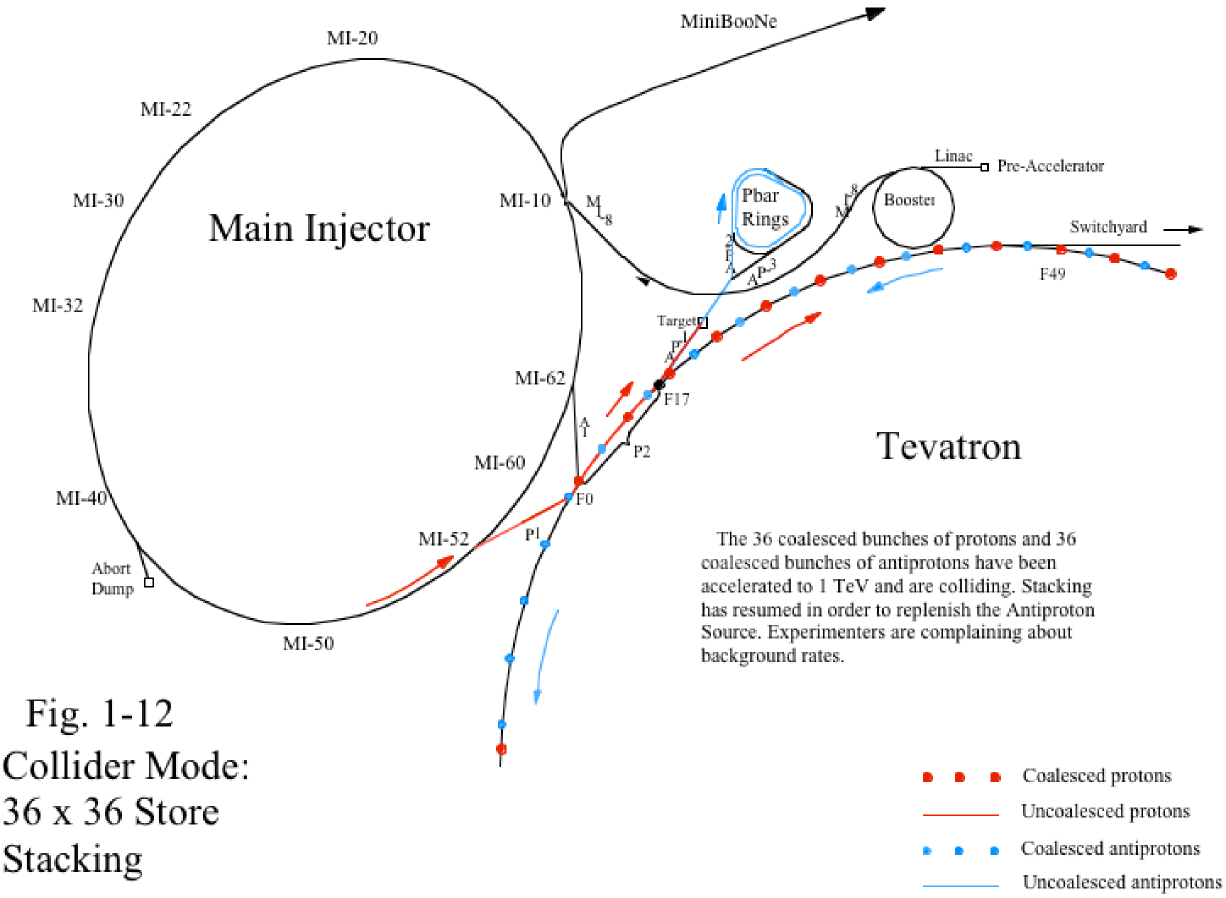


Fig. 1-12
Collider Mode:
36 x 36 Store
Stacking

Implicit in all of these maneuvers is the need for all of the coalesced bunches to be in the right place with respect to each other. This is accomplished by a technique called cogging, which in a rather abstract way resembles the cogs of intermeshing gears. Some cogging takes place in Main Injector and some occurs in the Tevatron. Cogging is one of the RF manipulations of the beam and will be discussed in a later chapter.

Role of the Recycler

The purpose of the Recycler is to store excess antiprotons. The number of antiprotons available has always been an important limiting factor in producing the high luminosities desired for stores in the Tevatron. They are difficult, or at least time-consuming, to produce—and if enough are created they are difficult to store because large numbers of antiprotons in the Accumulator tend to develop instabilities and can be suddenly lost.

The Recycler will store antiprotons from two sources: They can be siphoned off from large stacks, or they can be scavenged at the end of Tevatron stores. Both methods require the Main Injector as a middleman.

The Recycler ring is located directly above the Main Injector ring. Antiprotons are transferred from Main Injector to the Recycler through a beam line at MI-32. Transfer from the Recycler to Main Injector takes place at MI-22.

If the antiprotons are to come from the Accumulator, they will arrive in the same way as they would during a shot—through the AP-3 and AP-1 lines, into the P2 line at F17, and back through the P1 line, entering Main Injector at MI-52. Now, rather than being accelerated, they are transferred into the Recycler at MI-32.

Retrieving antiprotons from a store is a bit more involved, since the antiprotons are at 1 TeV. Here is a possible sequence of events, stepwise:

(1) The store has been circulating in the Tevatron for several hours. As particles are gradually lost and the beam size slowly grows, the luminosity degrades. At some point, a decision is made to terminate the store and load a fresh one.

(2) Scrapers, basically large chunks of metal, are slowly moved into the proton beam until only the antiprotons are left (the proton and antiproton orbits follow different paths in the Tevatron).

(3) The antiprotons are decelerated from 1 TeV to 150 GeV, using the Tevatron RF systems.

(4) A group of coalesced bunches of antiprotons is transferred from the Tevatron to Main Injector.

(5) While the antiprotons are still circulating at 150 GeV, they are "decoalesced"; that is, decomposed back into 7 or so bunches. If this is not done, they will probably not survive the trip down.

(6) The antiprotons are decelerated to 8 GeV.

(7) The antiprotons are transferred to the Recycler via the MI-32 line.

(8) The Main Injector is ramped back to 150 GeV and accepts a new group of coalesced bunches; decoalescing and deceleration follow.

(9) This continues until all of the antiprotons from the store are now in the Recycler.

The specifics of this plan may very well change as operational experience is gained. Be alert.

The Recycler has its own RF system to facilitate transfers to and from the Main Injector. It also, unlike Main Injector, has its own cooling systems. Cooling, in this sense, means reducing the random energy of the particles. Details of the Recycler RF and cooling systems will be made available in the Recycler Rookie Book.

Mixed Modes

There are those who wish to complicate the simple scenarios described in the preceding sections. For example, it might be possible to perform fixed target extraction and antiproton production simultaneously by accelerating six batches to 120 GeV, kicking one batch out toward the antiproton target, and resonantly extracting the remaining five. There would have to be an increase in the flattop time in order to accommodate both operations, but in the end it might be more efficient. History shows that at Fermilab, people want to do everything at once.

Two modes that are not compatible are Fixed Target extraction from the Tevatron and Collider Mode. Because of the many tunnel components that need to be changed, at least a few weeks are required to complete the switchover.

The details that have been so conveniently ignored over the last few pages will be addressed in the following chapters. Many different kinds of magnets are necessary to direct the beam where it is supposed to go; most of the magnets require power supplies and cooling water. There are vacuum systems to clear the beam pipe of the air molecules that would disrupt passage of the beam. The RF systems must not only accelerate two different kinds of particles, but also perform the complex manipulations of bunch rotation, cogging, and coalescing. Diagnostics must be present to analyze the beam. Control systems must ferry information to and from the thousands of individual components necessary to make the Main Injector function, and provide the precise timing required to keep them synchronized. Much more has to be said about the beam transport lines that connect one accelerator to another.

The next chapter, “Magnets and the Lattice,” will discuss in some detail how the various kinds of magnets maintain circulating beam in the Main Injector.